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Experimental Research on Sloshing System Based on Six Degrees of Freedom

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Abstract

In this paper, the experimental method is used to design the sloshing characteristics of an aircraft. The scheme can load three angular velocities and three linear velocities on the experimental platform, and can truly simulate the 6D trajectory model of an aircraft. Through the analysis of the test data, the slosh torque and slosh frequency generated by the fluid can be obtained.

Keywords

Sloshing system, Test scheme, Slosh torque, Slosh frequency.

1. Overview

For the aircraft filled with fluid medium, the flow in the rocket storage tank will slosh during the flight due to its own speed change, engine vibration, aerodynamic force, control force and other reasons, especially under some maneuverable flights, violent sloshing will occur.The force and moment of the fluid medium on the storage compartment during the sloshing process will affect the motion state of the rocket, change the flight dynamics of the rocket, and even cause serious accidents.Therefore, in the design process of the overall aircraft and control system, the influence of fluid sloshing in the storage tank must be considered, and effective anti-sloshing measures must be adopted to reduce sloshing.Generally, theoretical analysis is used to obtain the theoretical solution and effective anti-sloshing measures of the storage tank fluid sloshing through analytical and semi-analytical forms, and then the preliminary experimental research and analysis results are reviewed to quickly obtain the fluid sloshing characteristics and related parameters of the storage tank. To optimize the design of the attitude and orbit control system of the fluid aircraft.

Since the research object of sloshing dynamics of fluid-filled (such as liquid, liquid-solid) system is a nonlinear, unsteady, multi-degree of freedom coupled complex system, and fluid filling is mainly used in the aerospace field, and its application in rocket weapon systems are fewer, so there are fewer studies on the sloshing test of the storage compartment of the fluid aircraft.In this basic research project, we will combine theoretical analysis and experimental analysis methods to quickly analyze and study the sloshing characteristics of the fluid in the fluid aircraft storage cabin and the suppression of sloshing.The large amount of test data and sloshing parameters obtained through the previous sloshing test can more accurately refine and analyze the sloshing characteristics of the fluid in the storage tank, and use theoretical analysis methods and measures to guide the structural design to suppress sloshing, and quickly obtain the fluid sloshing characteristics of the storage tank and related parameters provide important reference and data support for the overall design and optimization of the sloshing rocket system and the attitude orbit control system.

Based on the experimental data of fluid sloshing performance of storage tanks with different structures for a certain project, this paper analyzes the sloshing characteristics of storage tanks in three-way translation, three-way rotation and coupled motion, and the effects of different structures on sloshing suppression.Relevant parameters are obtained through sloshing test data analysis, including sloshing frequency, sloshing moment, etc. Among them, the free decay test is to obtain the shaking frequency, and the forced shaking can obtain the shaking torque and other parameters. Obtain the effects of two different structural methods and different filling ratios on the sloshing characteristics of the storage compartment.Theoretical analysis is used to obtain the theoretical solutions of storage tank slopping of different structures through analytical and semi-analytical forms, and then the results of previous experimental research and analysis are reviewed to quickly obtain the fluid slopping characteristics and relevant parameters of the storage tank under the new anti-shaking structure, so as to optimize the design of storage tank anti-shaking structure.

2. The scheme design

2.1. Equivalent mechanical model

This article aims to measure the additional six-degree-of-freedom force and moment caused by the sloshing of the fluid during the movement of the container with fluid. In actual spacecraft mechanics analysis, stability research and control system design, it is usually desired to replace the complicated and time-consuming sloshing flow field calculations with simple and efficient mechanical models.Therefore, the equivalent mechanical model is needed to simulate the fluid sloshing dynamic behavior in the tank. Generally speaking, the fluid in the storage container consists of two parts: one part moves with the container and is called the rigid pulse mass, which is represented by a fixed mass; The other part shakes freely in the tank, called the convective mass, which is represented by a series of mass-springs or pendulums, which is the equivalent mechanical model.

The equivalent mechanical model includes the equivalent pendulum model and the equivalent mass-spring model. The construction of equivalent mechanical model is mainly based on the following four basic conditions:

1) The mass and moment of inertia of the equivalent mechanical model and the actual fluid are equal.

2) The equivalent mechanical model keeps the center of gravity basically unchanged when the fluid sloshes slightly.

3) The equivalent mechanical model and the fluid system have the same vibration mode and generate the same damping force.

4) The force and moment of a certain mode of the equivalent model under forced excitation are equal to the force and moment produced by the mode corresponding to the fluid sloshing. In general, the pendulum model and the mass-spring model are equivalent, but the pendulum model has nonlinear characteristics when the swing amplitude is large, and can be used for the study of nonlinear sloshing problems.

2.2. Experimental scheme design

The measurement scheme includes a measuring platform and tension sensor to complete the six-dimensional force measurement of the tested product. The system includes measurement coordinate system and missile coordinate system.

Measuring coordinate system

In order to facilitate the subsequent processing of the measured sensor data, the measurement coordinate system is defined on the upper panel of the measurement auxiliary tool; the coordinate origin is the midpoint of the upper panel of the tool, the coordinate system

OmXmYm is coplanar with the lateral sensor, and the Zm axis is vertically upward,forming the right hand system.

Projectile coordinate system

In order to better describe the fluid sloshing dynamics and moments of the projectile, the projectile coordinate system is established. Due to the fluid sloshing, the projectile's center of mass is not fixed. Take the center of the end face of the projectile's tail as the origin to establish a coordinate system OcXcYcZc, where the Xc axis is the body axis of the projectile, and the Zc axis is vertically upward, forming a right-hand system.

The formulas for calculating force F and moment M under the projectile coordinate system are as follows:FXc, FYc, FZc are the three directions of force measured by the sensor in the measurement coordinate system are converted into the three directions of the force in the projectile coordinate system, MXc, MYc , MZc are the moments in the three directions obtained in the projectile coordinate system.

$$\begin{cases} F_{Xc} = \sum F_{xi} \\ F_{Yc} = \sum F_{yi} \\ F_{Zc} = \sum F_{zi} \\ M_{Xc} = \sum M_{xi} \\ M_{Yc} = \sum M_{yi} \\ M_{Zc} = \sum M_{zi} \end{cases}$$

3. Experimental results and analysis

Excitation loading method: six degree of freedom XYZ three direction translation and one-way excitation loading with three-angle rotation of pitch, yaw, and roll angles, six degree of freedom coupled excitation loading.

3.1. Sloshing moment

The processing principle of shaking torque is as follows, and the processing result is shown in Figure 1.

1) Under the same excitation condition, record the system force and moment measurement data during the loading ratio test of different structures.

2) Smooth or filter the obtained test data

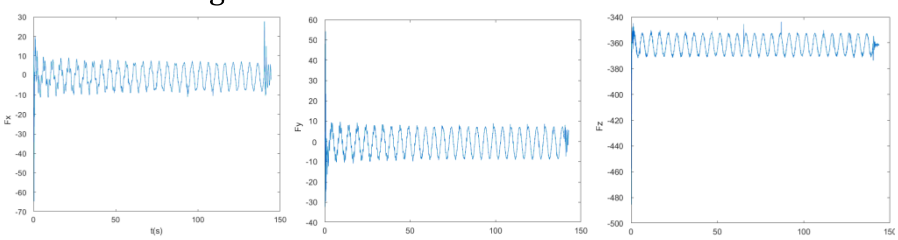
Smooth or filter the test data, remove the measurement outliers caused by sensors and other reasons, reduce the outliers interference, and facilitate subsequent processing.

3) Perform the first data fitting and constant term extraction

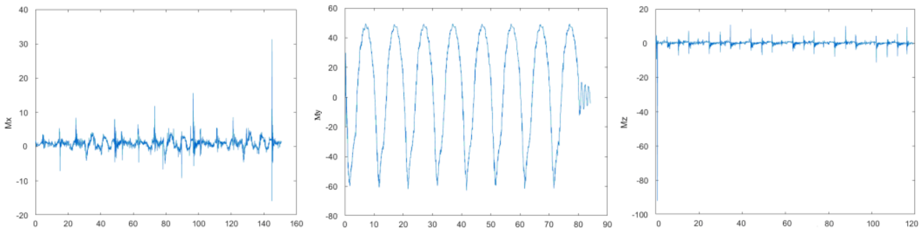
Use the fitting function to fit the filtered data, extract the constant term of the fitted curve, and subtract the constant term from the difference data.

4) Perform the second data fitting and peak extraction

Perform a second fitting on the obtained data, and extract the peak value of the fitted curve. Here, the peak value is considered to be the value of the sloshing force or sloshing moment generated by the fluid sloshing.



Fx-t Fy-t Fz-t



Mx-t My-t Mz-t

Figure 1Sloshing force and sloshing moment vary with time

3.2. Sloshing frequency

The shaking frequency processing principle is carried out as follows, and the processing result is shown in Figure 2.

1) Transform the data in the time domain recorded by the measurement system to obtain the data in the frequency domain

DFT (Discrete Fourier Transform) calculation principle:

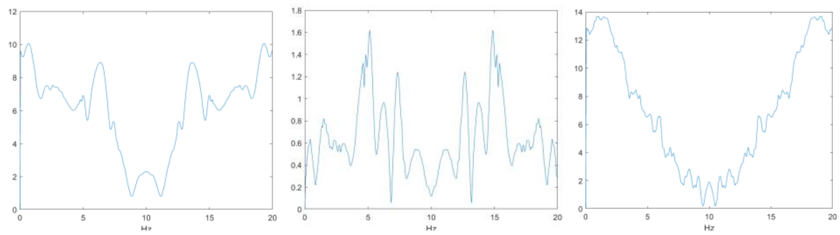
$$X(k)=\frac{1}{N}\sum_{n=0}^{N-1}x(n)\,e^{-j\pi nt/N}$$

In the formula: X(k) represents the data after DFT transformation, and x(n) is the analog signal obtained by sampling.

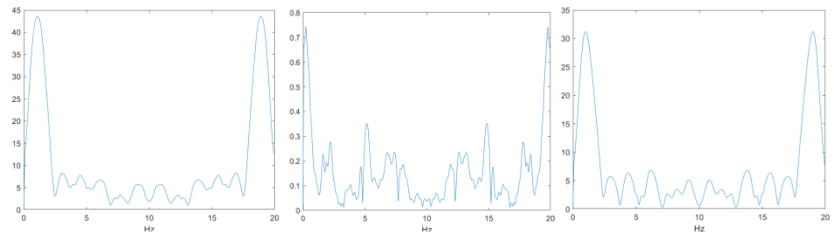
FFT is a fast algorithm form of DFT, which reduces the amount of calculation.

2) Extract the first-order main frequency from the spectrogram

The amount of data obtained after FFT transformation is the same as that before transformation, but half of the data is redundant, so the resulting spectrogram is symmetrical about the center frequency.



X direction of translationY direction of translationZ direction of translation



X direction of rotation Y direction of rotation Z direction of rotation

Figure 2Frequency changes in translation and rotation directions

4. Conclusion

The fluid sloshing test program can input the 6D parameters of the aircraft to test the force and moment of the fluid sloshing. Through the analysis of the test results, the sloshing frequency in all directions of the aircraft can be obtained. Through the above experimental analysis, the following conclusions can be drawn:

1) In each case of external excitation, there are components mainly affected by sloshing in each component of fluid sloshing force and sloshing moments. For example, under translational X excitation, the values of Fx and My are larger than other components;

2) In the case of the same applied external excitation form, the frequency of each component of the fluid sloshing force and sloshing moment is basically unchanged, and does not change with the amplitude of the applied external excitation;

3) It can be seen from the spectrogram of each component of sloshing force and sloshing moment that under each working condition, there is obvious main frequency information in the spectrogram of s the six sloshing force and moment components, and it can be considered that the component with obvious main frequency information is the main influence component of sloshing.

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